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ABSTRACT

We have demonstrated 466mW of 469nm light from a frequency doubled continuous wave fiber laser. The system consisted of a 938nm single frequency laser diode master oscillator, which was amplified in two stages to 5 Watts using cladding pumped Nd^{3+} fiber amplifiers and then frequency doubled in a single pass through periodically poled KTP. The 3cm long PPKTP crystal was made by Raicol Crystals Ltd. with a period of 5.9µm and had a phase match temperature of 47 degrees Centigrade. The beam was focused to a $1/e^2$ diameter in the crystal of 29 µm. Overall conversion efficiency was 11% and the results agreed well with standard models.

Our 938nm fiber amplifier design minimizes amplified spontaneous emission at 1088nm by employing an optimized core to cladding size ratio. This design allows the 3-level transition to operate at high inversion, thus making it competitive with the 1088nm 4-level transition. We have also carefully chosen the fiber coil diameter to help suppress propagation of wavelengths longer than 938 nm. At 2 Watts, the 938nm laser had an M^2 of 1.1 and good polarization (correctable with a quarter and half wave plate to >10:1).

INTRODUCTION

With the continued interest in development of solid-state blue laser sources [1,2,3] we would like to show that fiber lasers and nonlinear frequency conversion are an attractive approach. Fiber sources are a good choice for nonlinear frequency conversion because of their good beam quality and high brightness [4]. Using non-critical phase matching eliminates the problems of spatial walk off allowing for longer interaction lengths and this leads to higher conversion efficiency.

Our fiber amplifier uses the $^4F_{3/2}$-$^4I_{9/2}$ transition in neodymium and because of the 3-level nature of the transition there is strong competition from the $^4F_{3/2}$-$^4I_{11/2}$ 4-level transition. Optical fiber hosts have the advantage of wavelength selective loss [5] dependent on bend diameter allowing the user to choose a fiber coil diameter to act as a variable short pass filter. In our case we were able to choose a coil diameter that will generate ~10dB of loss for the competing 4 level 1088 nm parasitic transition while generating very little loss at 938 nm.

High power levels have been achieved for this Neodymium transition in crystal hosts [6] however to our knowledge this is the highest power achieved for this transition in a silica fiber host [7]. The silica host offers a broader absorption spectrum reducing the precision requirements of the pump and a broader emission spectrum (900nm to 950nm) enabling more applications. We have previously reported multi-watt operation on this transition [8] and continue investigating power scalability.

While the idea of quasi-phase matching has been around for a long time [9] engineered nonlinear materials are starting to gain maturity and are commonly used for nonlinear frequency conversion. A lot of progress has been made in both materials and periodic structure fabrication in recent years. Fabricating the short periods required for first order frequency doubling into the blue still remains challenging. Because of its anisotropic lattice structure $KTiOPO_4$ (KTP) exhibits very limited domain wall spreading during the poling process leading to the ability to pole very short domain periods. Also the KTP has a coercive voltage about 10 times lower than congruent $LiNbO_3$ enabling electric field poling of thicker materials.

1. Experimental set up

Our system consisted of a laser diode as the initial oscillator that was amplified in two stages of Nd fiber amplifiers. The amplified signal was then focused into a 3 cm long PPKTP crystal to complete the frequency conversion. The 938nm oscillator was a 200mW laser diode made by Axcel Photonics Inc. The laser diode output was collimated with a single 4.5mm focal length aspheric lens. The collimated beam size incident upon the lens used to focus it into the fiber was roughly a 1mm X 3mm spot . A noise source was connected to the diode through a bias tee to increase the diode oscillator bandwidth from 4.4 KHz to ~1Mhz. Since the laser diode is the original seed source for both the first and second stage fiber amplifiers we wanted to put some bandwidth on it in an effort to prevent the onset of stimulated Brillioun scattering. The initial noise generator in our system has a fixed level and the amplitude of noise superimposed upon the diode drive current is adjusted through a variable attenuator. A lower attenuation level will relate to an increase in the noise output level (or less attenuation of the noise source) applied to the diode current thereby increasing the laser diode bandwidth. The line width was measured with a scanning Fabry Perot interferometer and a plot of the line width verses the noise generator attenuation is shown below.

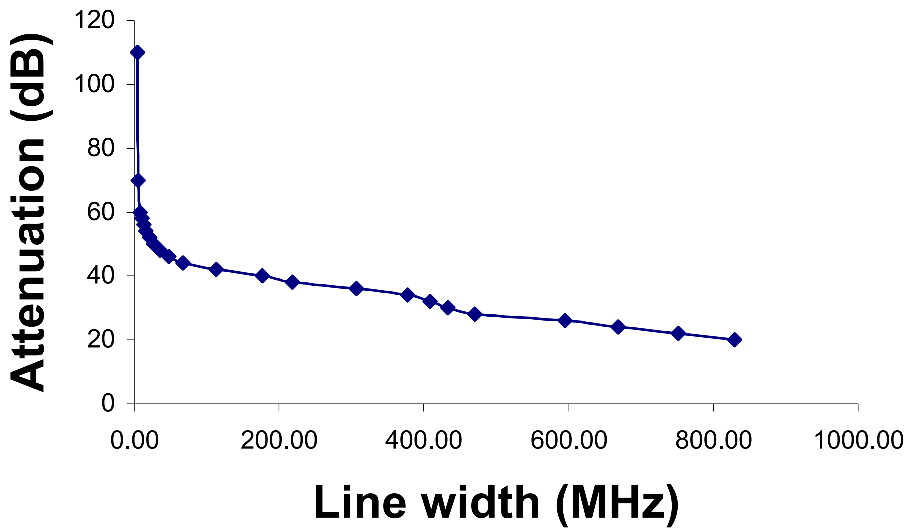

Figure 1. The laser diode line width vs. noise generator attenuation

During the warm up of the system the laser diode was somewhat prone to mode hops and frequency drift that caused the nonlinear phase matching temperature to move with changing oscillator frequency. During all of the measurements that we made, the frequency of the oscillator was monitored with an optical spectrum analyzer to ensure frequency stability over the course of each measurement. It would be preferable to use a distributed feedback section of delivery fiber or a diffraction grating to provide some optical feedback to stabilize the frequency. The collimated diode oscillator was focused into the core of our stage first fiber amplifier with ~ 40% coupling efficiency. Since we used a single lens for collimating the diode oscillator the beam is highly elliptical causing the rather poor coupling efficiency.

The first stage amplifier consisted of 27 meters of double clad Nd doped fiber that was pumped by a 25 Watt fiber coupled (200 μm, 0.22 numerical aperture) laser diode array at 800nm made by LIMO–Lissotschenko Mikrooptik, GmbH. The transport fiber was purchased from Richard Losch Inc. and provided very high transport efficiency. We used a 10-degree angle of incidence dichroic to transmit the pump light from the transport fiber and reflect the amplified signal. We chose this shallow angle to minimize polarization dependent reflections due to the unpolarized nature of light from the pump transport fiber.

The core diameter of the double clad amplifier fiber was 20 μm with a .06 NA and a 100 μm pump cladding diameter. The first stage amplifier output was single mode with a polarization extinction ratio of 15:1 after a quarter and half wave plate combination. The M^2 was ~1.1 measured at 1.3 Watts and the amplifier provided a gain of 10 dB. The linear polarization gave us less than 15% loss through the first stage bulk polarizing isolator. A single 8mm focal length lens used to both focus the pump and collimate the amplified signal. Due to the difference in NA between the fiber amplifier core and the pump cladding we chose to optimize the pump coupling. By doing this, the amplified signal is slightly divergent so this must be taken into account in the choice of distance between the two fiber amplifier stages and the signal coupling lens between amplifier stages.

The second stage amplifier consisted of 36 meters of double clad Nd doped amplifier fiber with the same specifications as the first stage. This was pumped with a fiber coupled laser diode array made by Apollo lasers that also used a 200 µm diameter and 0.22 NA transport fiber. The coupling from the first stage fiber amplifier into the core of the second stage fiber amplifier was 67% giving ~ 875mW of seed light in the fiber. The amplified signal from the second stage was 6 Watts at 938nm with 50W of incident pump or just over 8 dB of gain. A cooling fan was used to cool the second stage fiber coil that sat on an aluminum heat sink. The pump end of the second stage fiber was held in a water-cooled copper fiber chuck.

After the second stage optical isolator a 300mm focal length lens was used to fine-tune the collimation before the final focusing lens into the nonlinear crystal. The turning mirror that we positioned after the final collimation lens was identical to the dichroic mirrors used between the fiber amplifier stages so it provided good transmission of any residual pump light as well as any 1088nm light that made it through the isolator.

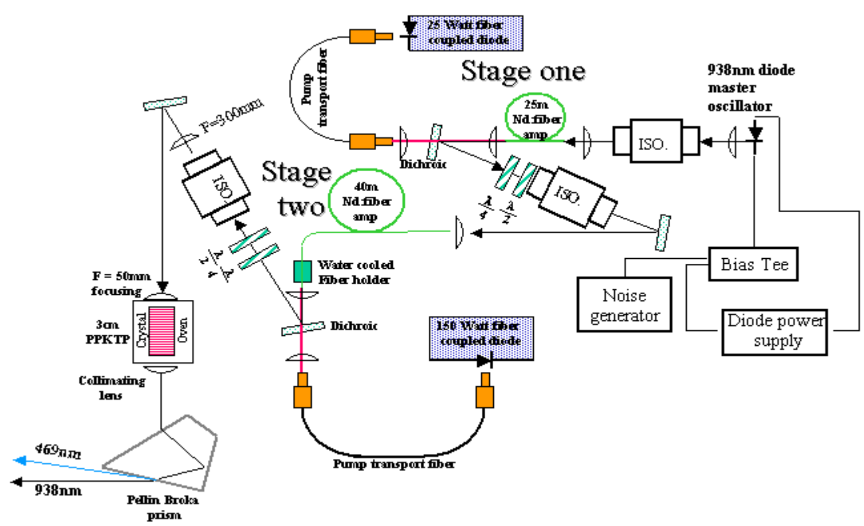

Figure 1. Schematic of the 938nm oscillator, cladding pumped optical fiber system, frequency conversion crystal and wavelength separation

Our frequency doubling crystal was a 1mm x 2mm x 3cm long PPKTP crystal used in a single pass configuration with a poling period of 5.9µm made by Raicol Crystals Ltd. The crystal was anti-reflection coated for both fundamental and second harmonic wavelengths on both ends. The incident fundamental beam was measured with a Modemaster beam analyzer positioned with the front plane of the beam analyzer where the focusing lens would eventually be located. The incident beam had good symmetry with an M^2 of 1.1 and good collimation. The beam was then focused with a 5 cm focal length lens and measured using the knife edge technique at various points along the propagation axis. The focused spot size matched our calculations based upon the measured spot size at the lens. The PPKTP crystal and oven were then put in place and aligned for the best conversion at low power. After the doubling crystal we positioned a lens with a visible antireflection coating to collimate the output. The collinear fundamental and second harmonic beams where then separated with a Pellin Broca Prism and an aperture was used to spatially filter out the fundamental for the final power measurement.

2. Experimental results

We changed the lens used to focus into the nonlinear crystal to a 10cm focal length to create a focus that matched the confocal parameter for our crystal length and measured the phase match curve. This data was then normalized and the experimental points were fitted to a theoretical curve for second harmonic generation used by V.G. Dmitriev et al.[10]. By adjusting the calculated crystal length to best fit the measured data we arrived at an "effective length" of 2.5cm. This process is useful in understanding several parameters of the crystal quality. The following figure contains the experimental data and calculated fit resulting in the determination of our effective crystal length. We then tightened our focus with a 5cm focal length lens adjusting the spot size for the best conversion in the crystal. After measuring the conversion vs. temperature curve and determining the best phase matching temperature we adjusted our focus for the best conversion. This was determined by using the focusing parameters described by Boyd and Kleinman [11].

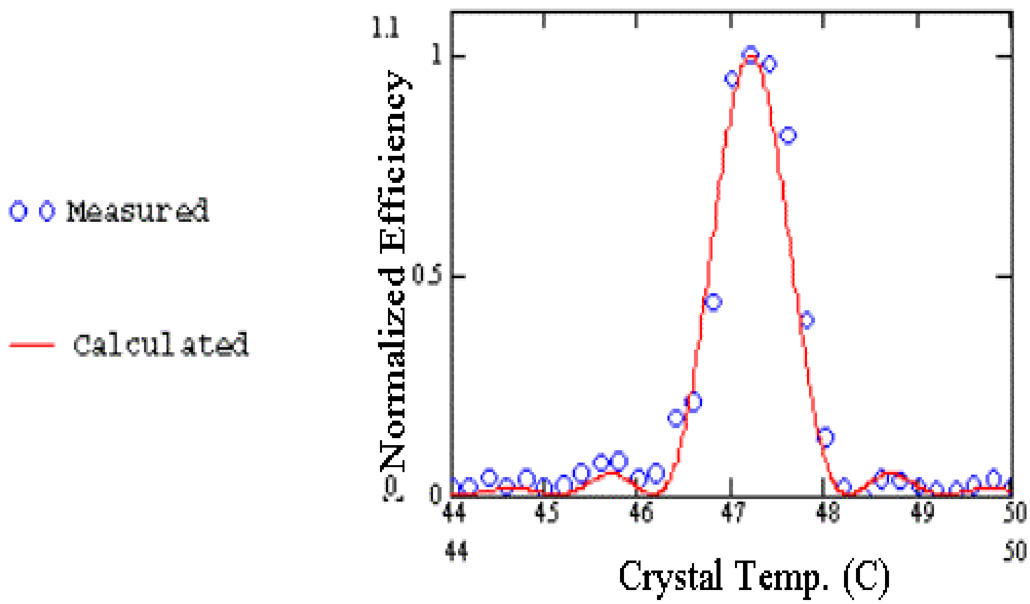

Figure 2. Plot of the normalized phase matching efficiency as a function of crystal temperature. Experimental data is shown with blue circles and the theoretical fit for a 25mm crystal is shown in red.

With an incident fundamental power of 4.56 watts we measured 466mW of 469nm of frequency doubled power. This equates to a single pass conversion efficiency of greater than 10 percent or 2.2 percent per Watt. Although this was our highest power achieved the best conversion efficiency was with an incident power of 3.82 Watts for a second harmonic power of 422mW and a conversion efficiency of 11.1 percent or 2.9 percent per Watt.

As can be noted in figure 2 (above) the effective crystal length as derived from the theoretical fit is 5mm shorter than our actual crystal length. The measured ratio between the fundamental and second harmonic powers shows some degradation at higher powers levels. The following chart shows the second harmonic power as a function of incident power and indicates the lower conversion efficiency at higher powers rather than a quadratic increase.

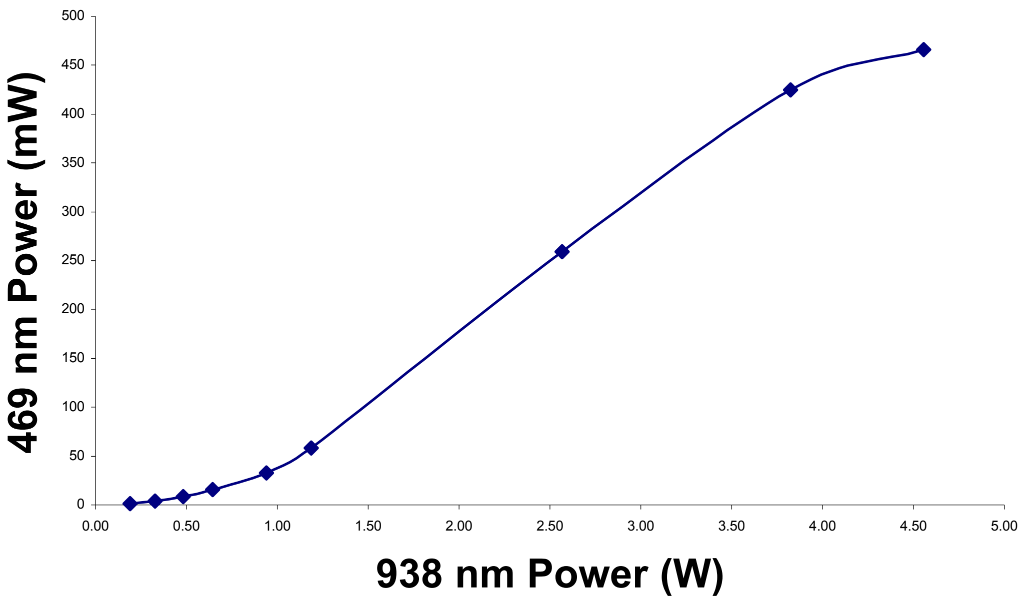

Figure 3. This is a graph of the measured 469nm power as a function of the incident 938nm power.

We did not see any appreciable degradation in a similar 3cm long PPKTP crystal that we used at similar power levels for sum frequency generation at 589nm over a 100-hour period. We did not measure the blue second harmonic output vs. time. However did see some evidence of roll off at the higher powers for frequency doubling to 469nm. As we increased the incident power the oven temperature had to be reduced to retain phase matched suggesting possible optical absorption in this particular crystal.

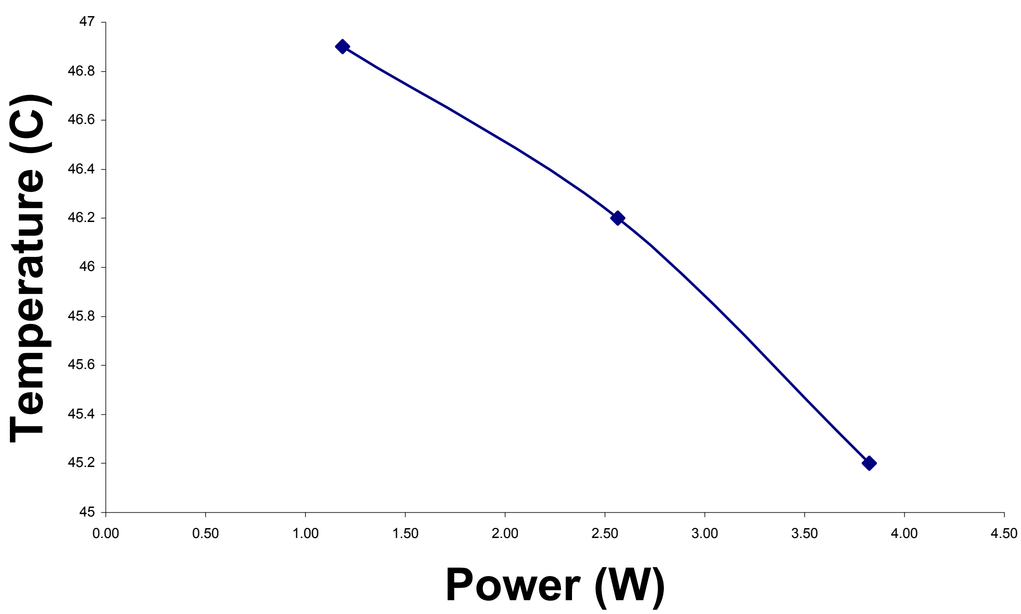

Figure 4. The crystal oven temperature for optimum SHG power decreased as a function of incident power.

3. Conclusion

We were able to generate nearly one half of a Watt of 469nm light from the second harmonic conversion of a 938nm Nd fiber amplifier system. We measured one sample of PPKTP and although we did see some degradation in frequency conversion efficiency at higher powers the system has shown the potential to reach new wavelengths with good power and efficiency. We have demonstrated the beam quality and versatility of fiber amplifiers combine with the efficient frequency conversion of periodically poled nonlinear crystals as a method of achieving new wavelengths.

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